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Impact of the electricity mix and use profile in the life-cycle assessment of electric vehicles

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ABSTRACT

This paper presents an environmental and an economic Life-Cycle Assessment (LCA) for conventional and electric vehicle technologies, focusing mainly on the primary energy source and the vehicle operation phase Greenhouse Gas (GHG) emissions. A detailed analysis of the electricity mix was performed, based on the contribution of each type of primary energy source and their variation along a year. Three mixes were considered, with different life cycle GHG intensity: one mainly based in fossil sources, a second one with a large contribution from nuclear and a third one with a significant share of renewable energy sources. The conventional vehicle technology is represented by gasoline and diesel International Combustion Engine Vehicles (ICEVs), while the electric technology is represented by Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs). Real world tests were performed for representative compact and sub-compact EVs. The use profile of the vehicle was based on data acquired by a real time data acquisition system installed in the vehicles. The results show that a mix with a large contribution from Renewable Energy Sources (RESs) does not always translate directly into low GHG emissions for EVs due to the high variability of these sources. The driving profile under different scenarios was also analyzed, showing that an aggressive style can increase the energy consumption by 47%. The tests also showed that the use of climate control can increase the energy consumption between 24 and 60%. Compared with other technologies, EVs can be more sustainable from an environmental and economic perspective; however, three main factors are required: improvement of battery technology, an eco-driving attitude and an environmental friendly electricity mix.

Contents

Abbreviations: AC, Alternate Current; AFV, Alternative Fuel Vehicle; BEV, Battery Electric Vehicle; BMS, Battery Management System; CNG, Compressed Natural Gas; DOD, Depth of Discharge; ESS, Energy Storage System; EC, European Commission; EU, European Union; EV, Electric Vehicle; FC, Fuel Cell; FCEV, Fuel Cell Electric Vehicle; FTP-75, Federal Test Procedure 75; GWP, Global Warming Potential; GHG, Greenhouse Gas; HEV, Hybrid Electric Vehicle; HFCV, Hydrogen Fuel Cell Vehicle; ICE, Internal Combustion Engine; ICEV, Internal Combustion Engine Vehicle; IMU, Inertial Measurement Unit; IEA, International Energy Agency; LCA, Life-Cycle Assessment; LNG, Liquefied Natural Gas; LPG, Liquefied Petroleum Gas; MFI, Maintenance, Fuel, Insurance; MRT, Maintenance, Repair, Insurance and Taxes; NEDC, New European Drive Cycle; PEM, Power Electronics Module; PHEV, Plug-in Hybrid Electric Vehicle; PM, Particulate Matter; PT, Powertrain; RES, Renewable Energy Source; SFTP, Supplemental Federal Test Procedures; SOC, State of Charge; TCO, Total Cost of Ownership; TTW, Tank-to-Wheel; WTT, Well-to-Tank; WTW, Well-to-Wheel

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1. Introduction

Climate change is more than ever a driving force on different aspects of today's society. People are becoming increasingly aware of the real impacts of this change and want to play an active part in the mitigation of this issue. The search for more energy efficient and environmentally friendly products can also translate into a reduction of the energy bill.

The transport sector is a major contributor of carbon dioxide emissions and EVs are becoming more relevant on the future of the transport system, for the Governments around the world, due to their potential to reduce GHG emissions and increase energy security [1]. With access to a more accessible mobility, the demand for new vehicles is rising rapidly and vehicle numbers are estimated to more than double before 2050, with highest growth rates in developing countries [2–4]. In the absence of new legislation or policies that may affect the energy market, the transport energy use and associated GHG emissions, are projected to increase by 46% in 2035, compared to 2005 values, accounting for 82% of the total increase in liquid fuel consumption, while the use of liquid fuels for electric power generation declines [5]. To limit the rise of the global long term mean temperature by 2 °C, a 50–85% reduction of GHG emissions, compared to 2000 levels, has been proposed [6].

To meet the increasing demand for transport and at the same time reduce GHG emissions and improve air quality, the paradigm of personal transportation has to change. This change embraces alternative vehicle and fuel technology as well a smarter infrastructure, through the electrification of the powertrain, using batteries or fuel cells, and the use of alternative fuels, such as biofuels, natural gas and hydrogen [7–9].

Alternative Fuel Vehicles (AFVs), such as those powered by Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG) and Liquefied Petroleum Gas (LPG) are also other viable low-carbon alternatives. These are in hand with conventional ICE vehicles in terms of environmental impacts, associated with the production and disposal. The additional impacts during the production and disposal phase come from the additional material required for the gas reservoir. In terms of investment, these vehicles are 5–10% more expensive than the conventional vehicles but present lower operating costs, due to the lower cost of the fuel. During the operation phase, these vehicles have lower GHG emissions when compared with conventional ICEVs, with a significant reduction in particle emissions [10–12]. However, some studies also shown an increase in NO_x and CO depending on the driving cycle [13–15]. A key aspect that should also be taken into account is the GHG upstream emissions, which vary with the fuel production process and geographic location, which could offset the GHG savings.

Hydrogen Fuel Cell Vehicles (HFCVs) are similar to BEVs in terms of having a high efficiency powertrain. A key difference between both technologies is the upstream GHG emissions associated with the generation and delivery of the energy carrier [16]. Two key aspects that affect the viability of HFCVs are related with the hydrogen storage and production [17]. In [18,19] several hydrogen production and storage technologies are studied from a Well-to-Tank (WTT) perspective. Despite some of them contribute to lower Well-to-Wheel (WTW) GHG emissions, the added cost associated with does not enable the massification of the technology. Due to the energy intensive process of producing hydrogen by hydrolysis, a HFCV will require up to three times more energy and will emit three time more GHG than a BEV [11]. However, the use of HFCVs in a scenario where electricity is obtained from RESs could have advantages over BEVs to achieve a higher autonomy.

Improvements in conventional Internal Combustion Engine (ICE) technology can reduce petroleum demand, however efficiency alone cannot reduce GHG emissions to levels 80% below 1990 for the light vehicles fleet. The cost and availability of low GHG fuels will impose limits to their use. To achieve significant reductions in GHG emissions the future transport systems will require optimized combinations of advanced fuels and vehicle technologies [11].

Powertrain electrification is seen has the solution to a more sustainable transport system that can contribute to a reduction of GHG emissions and the import of crude oil, due to a much higher efficiency, from 28–30% of an ICEV to 74–85% of an EV, and zero tailpipe emissions [20], however due to a higher initial cost when compared with conventional technology, taking several years to offset the investment, their penetration on the market is expected be slow [21].

The presence of an energy storage device allows the EVs to be used as a flexible load and to support large scale renewable energy generation through smart recharging methodologies, however the massive electrification of the vehicles may bring additional problems to the electric grid if not correctly managed [22,23]. Despite the use of electricity as the energy source for EVs and zero tailpipe emissions, it is fundamental to assess these vehicles in terms of economic, energy consumption and GHG emissions, taking into account not only the vehicle LCA but also the electricity generation [24].

The contribution of EVs to reduce GHG emissions must be assessed by using a cradle-to-grave perspective for the vehicles and WTW for energy carries. In this context, a comparative LCA can be performed for ICEVs and EVs. This type of assessment allows a detailed comparison between several vehicle technologies and the identification of opportunities of technological development and improvement in the life-cycle phase of a vehicle. In this LCA, the vehicle technology analyzed was the conventional motorization, represented by both gasoline and diesel ICEVs, and electric vehicle technology represented by PHEVs and BEVs. Fuel Cell Electric Vehicles (FCEVs) were not considered in this study due to high cost and technical issues with this type of technology that still need to be addressed, such as hydrogen capture, storage and distribution, limiting their widespread adoption [7,25,26]. Since the EVs environmental impact is directly related to the electricity generation mix, several scenarios from the European Union (EU) were considered based on the renewable, nuclear and fossil fuel share.

2. Life-cycle model and system boundary

The model and respective system boundaries for each vehicle technology (ICEV, PHEV and BEV) are presented on Fig. 1. A global

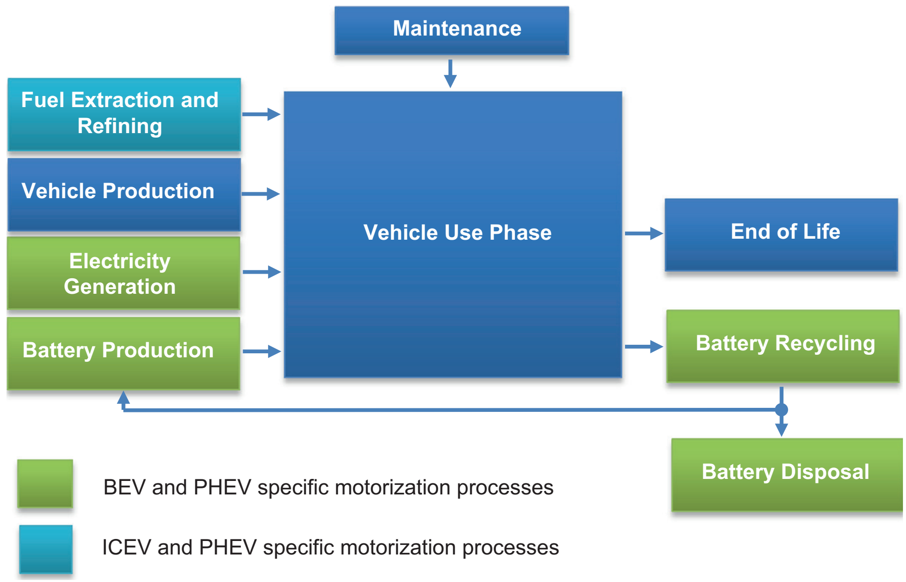

Fig. 1. Model and system boundaries for the three vehicle technologies.

Table 1
Characteristics of the vehicles considered for each category.

Characteristics	ICEV				PHEV	BEV		
	VW Golf 1.6 TDI	VW Golf 1.4 TSI	Smart CDI	Smart	Chevrolet Volt	Nissan Leaf	Smart ED	Peugeot iOn
Emissions (gCO_2/km)	118	144	98	86	0(ED) 160(GD) 91(MD)	–	–	–
Fuel consumption (l/100 km)	4.2	6.2	3.3	4.2	-(ED) 6.9(GD) 3.9(MD)	–	–	–
Electricity consumption (Wh/km)	–	–	–	–	140	140	110	120
Combustion engine (cc)	1600	1400	800	1000	1400	–	–	–
Electric motor (kW)	–	–	–	–	111	80	30	47
Battery capacity (kW h)	–	–	–	–	16	24	16.5	16
Battery weight (kg)	–	–	–	–	197	300	140	200
Battery type	–	–	–	–	Li-Ion	Li-Ion	Li-Ion	Li-Ion
Range (km)	700+	700+	500+	500+	580 (80ED + 500ER)	160	135	120
Curb weight (kg)	1240	1290	770	750	1715	1521	870	1080

Note: For the PHEV were considered three driving scenarios: only gasoline drive (GD), only electric drive (ED) and mixed drive (MD). The fuel consumption is given for the vehicle running with the battery depleted.

perspective is considered over the vehicles life-cycle and their key components, such as the battery, as well the electricity generation. The manufacturing phase was considered common to all vehicles and calculated based on the vehicle weight. An additional burden, due to the use of a battery, was added to the EVs based on battery weight.

Several LCA studies show that the most critical phase in terms of GHG emissions is typically the operation phase, whether it be a conventional or electric vehicle [27]. The exception is for BEVs charged with electricity in a mix with low GHG emissions, where the production phase is the most critical. Gasoline and diesel ICEVs have the higher emissions during the operation phase followed by PHEVs and BEVs while the emissions during the production phase are similar to all vehicle technologies, excluding the battery production. During the vehicle production, the battery used in PHEVs and BEVs is the most critical component in terms of GHG emissions, contributing with 30–50% of total emissions, mainly due to the materials and quantities required for the battery production [28–30,27].

During the vehicle use phase, for the BEV and for the PHEV the vehicle Tank-to-Wheel (TTW) efficiency was taken into account as well real world driving profiles. GHG emissions associated with the infrastructure for crude oil processing, transport and distribution as well for electricity generation were also considered. The production and end of life phases for the considered vehicle technology were based on [31], while the battery LCA inventory was based on [29,32]. The LCA database for the considered vehicles was created using the Ecoinvent dataset [33]. This LCA intends to provide a comparison between EVs and ICEVs over their entire life-cycle and also assess the impact due to the use profile of the vehicle and energy source. This type of analyze allows the identify of the most critical aspects in terms of emissions and where actions can be taken in order to reduce them.

2.1. Vehicle characteristics and assumptions

The vehicle technology addressed were ICEVs, PHEVs and BEVs. ICEVs (both diesel and gasoline) were used as a baseline for the impact assessment of the other vehicle technology considered. Based on market relevance, the ICEV is represented by the Volkswagen Golf (best seller in the European market), both for the gasoline and diesel version, the PHEV and BEV are represented by the Chevrolet Volt and by the Nissan Leaf respectively. Since subcompact vehicles are becoming more popular in a urban environment, two electric vehicles that fit in this category were also considered, represented by the Smart ED and Peugeot iOn (also sold in Europe re-branded as the Mitsubishi i-MiEV and Citroën C-Zero). Since the Smart ED fits in a different category when compared with the other vehicles considered, both diesel and gasoline versions were included to be used as a comparison base. The vehicle main characteristics are listed on Table 1, based on manufacturer data and average cost in the European market [34].

To correctly assess the impact of vehicle in terms of GHG emissions during the use phase, the energy losses in a vehicle need to be characterized. For ICEVs these losses are translated directly to fuel consumption, however since BEVs and PHEVs require energy from the grid to charge the batteries, the additional losses in the transmission and distribution system must be accounted for, usually around 9–10% [35–37]. For instance, to charge a 16 kW h battery connected to a power grid with an efficiency of 90% it will require a generation of 17.6 kW h.

In a EVs, energy losses occur in the energy storage system (usually a battery), at the drivetrain (the group of mechanical components responsible to transmit the power from the motor to the wheels to propel the vehicle) and in the power electronic module (responsible for the motor control, regenerative braking and charging) [38,39].

The energy storage system can be constituted by batteries, supercapacitors or by the combination of them. Nowadays, the battery is the main component of the Energy Storage System (ESS) due to a lower cost when compared with other storage technologies [40–43]. Lithium-Ion batteries are the most common in EVs due to a specific energy up to 400 Wh/kg and a high specific power (up to 10 kW/kg) when compared with lead-acid batteries, which have a specific energy density between 20 and 30 Wh/kg and a specific power up to 400 W/kg [44]. The batteries used in EVs have an energy capacity in the range of 10–85 kW h and an efficiency of about 70%–95% [45]. Internal resistance, typically in the range of milliohms, which increases both with cycling and age, is one parameter that contributes to the battery efficiency by causing a voltage drop under load and by reducing the maximum output current affecting the charge/discharge rate [46–48].

Battery life and capacity are key aspects for the wide adoption of electric vehicles. To estimate the potential savings in terms of GHG emissions and also the Total Cost of Ownership (TCO) of a vehicle it is fundamental to estimate the life of a battery under real world operation. The battery state of health is greatly influenced by the load and environmental conditions [49,50]. Depending on the lithium-ion cell chemistry, both high and low State of Charge (SOC) contribute to the deterioration of the battery performance and lifetime. Overcharge, over-discharge, high Depth of Discharge (DOD)s and high temperatures also influence the fast decay of the battery life and low temperatures can also have a negative impact, mainly during the charging phase [46,51].

Modern electric vehicles employ Battery Management System (BMS) that monitor the battery state of health and avoid working points that contribute to accelerated aging, for instance by controlling the battery pack temperature using active heating and cooling systems, as well as by avoiding the battery overcharge and over-discharge. Depth of discharge is also managed by limiting the amount of energy that can be drawn (from a 24 kW h pack, only 20 kW h or less are used). It is expected, that the battery, managed by the BMS, working within specified boundaries will last, with a high degree of probability, the life time of a vehicle. The user can also contribute to the mitigation of the aging effects by avoiding complete battery charge/discharge cycles and by minimizing the load applied to the battery due to fast accelerations, by adopting an eco-driving profile.

The powertrain includes the Internal ICE and/or electric motor, transmission, drive shaft, differential and drive wheels. In the case of diesel ICEs, the efficiency is around 30–35% in the ideal speed range, declining outside this range, while gasoline ICEs have an efficiency of 18–25%, meaning that around 80% of available energy is lost as heat.

In EVs, the most common types of electric motors are permanent magnet motors and induction motors with an efficiency, depending on the type of motor, that can go from 85% up to 95% from a wide speed range [52].

In the drivetrain, responsible by the transmission of the mechanical energy generated by the engine to the road, the energy losses occur in the differential and final drive. In an ICEV, the oil pump is responsible for 30–40% of total power loss, the clutch contributes with additional 20–25% and gear meshing, bearings, bushings and drag on the gears caused by the gear oil are responsible for the additional losses. In the case of rear and all-wheel drive vehicles the power losses in the differential tend to be larger due to a 90° turn in the torque path and are usually 6–10%, while losses from the drive shaft are 0.5–1% of total losses [53,36]. The total losses in the drivetrain account around 5–8%.

One characteristic of electric motors is the ability to supply the maximum amount of torque over a very large range of speeds, eliminating the need for gear shifting in EVs and giving the vehicle a smoother acceleration and braking. The mechanical power is

Table 2
WTW system efficiency for the electric powertrain, considering the power losses along the electricity path, using a DC fast charger (DC) and a standard 240 VAC charger (L2), with Lithium-Ion batteries as energy storage. It should be noted that for the overall system efficiency the battery efficiency was accounted twice due to the charge and discharge cycles.

System components	Global system efficiency (%)	
	Minimum	Maximum
Transmission	98	99
Distribution	91	93
L2 Charger (L2)	95	97
DC Fast Charge (DC)	91	94
Battery	90	95
Inverter	90	98
Electric Motor	85	96
Drivetrain	87	93
WTT (w/L2)	76.2	84.8
WTT (w/DC)	73.0	82.2
TTW	59.9	83.1

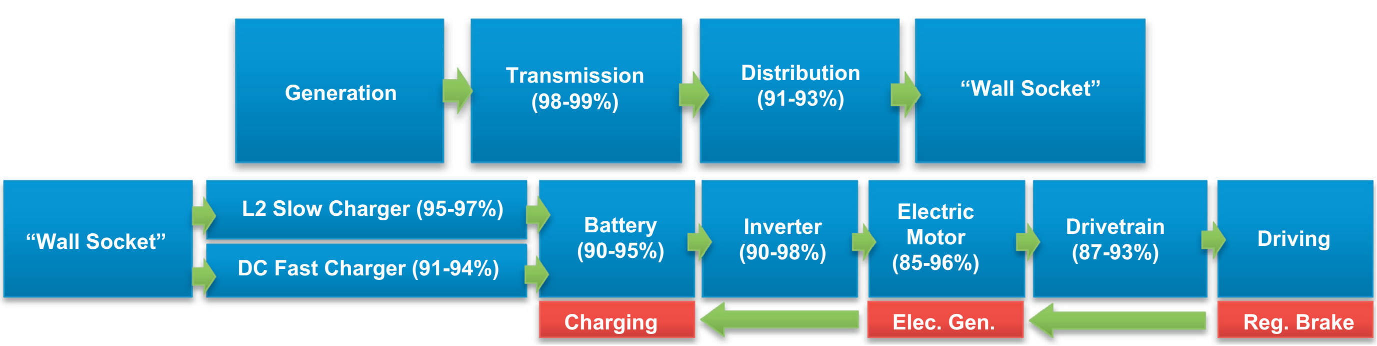

Fig. 2. Range of efficiency of the different components in the energy path of an EV.

delivered directly, or through a simple gear reduction step to the main-shaft of the transmission, so the only loss sources are windage, friction and drag, resulting in total at-the-wheel losses as low as 1.5% to 2%. The Power Electronics Module (PEM) controls the energy flow from the battery to the motor and vice versa. The main component is an inverter with an efficiency of 90-98%. Other component to be taken into account, both for PHEVs and BEVs efficiency, is the charger typically with 91–97% efficiency. Fig. 2 shows the conversion path of energy, from generation to the wheels.

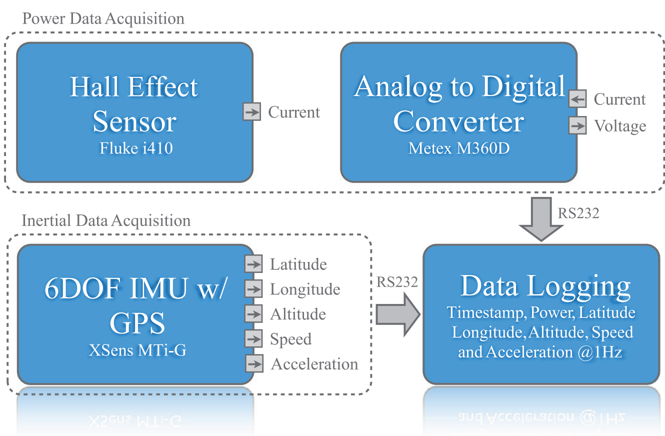

Fig. 3. Data acquisition system installed on the EVs [55].

Table 2 summarizes the efficiency of each system along the energy path to power an EV. WTT and TTW efficiency was calculated using (1) and (2).

$$\eta_{WTT} = \eta_{trans.} \cdot \eta_{dist.} \cdot \eta_{charger} \cdot \eta_{batt.} \tag{1}$$

$$\eta_{TTW} = \eta_{batt.} \cdot \eta_{inv.} \cdot \eta_{electricMotor} \cdot \eta_{trans.} \tag{2}$$

2.2. Use phase and main factors that contribute to EVs energy consumption

The phase during the vehicle life-cycle that dominates the overall GHG emissions is generally the use phase, regardless of the type of vehicle, being the gasoline ICEV the one with a higher environmental impact, according to several LCA studies [28,54,55], therefore its characterization with a high degree of accuracy is desirable. Usually the emissions from motor vehicles are based in specific drive cycles approved by Governmental entities, such as New European Drive Cycle (NEDC) in Europe or FTP-75 in USA, to assess vehicle fuel consumption, performance and emissions [56]. These type of cycles are important since they compare and check if a specific vehicle meet Government requirements. However they do not take into account some factors that contribute heavily to a vehicle energy consumption, such as the path elevation profile and the driving profile.

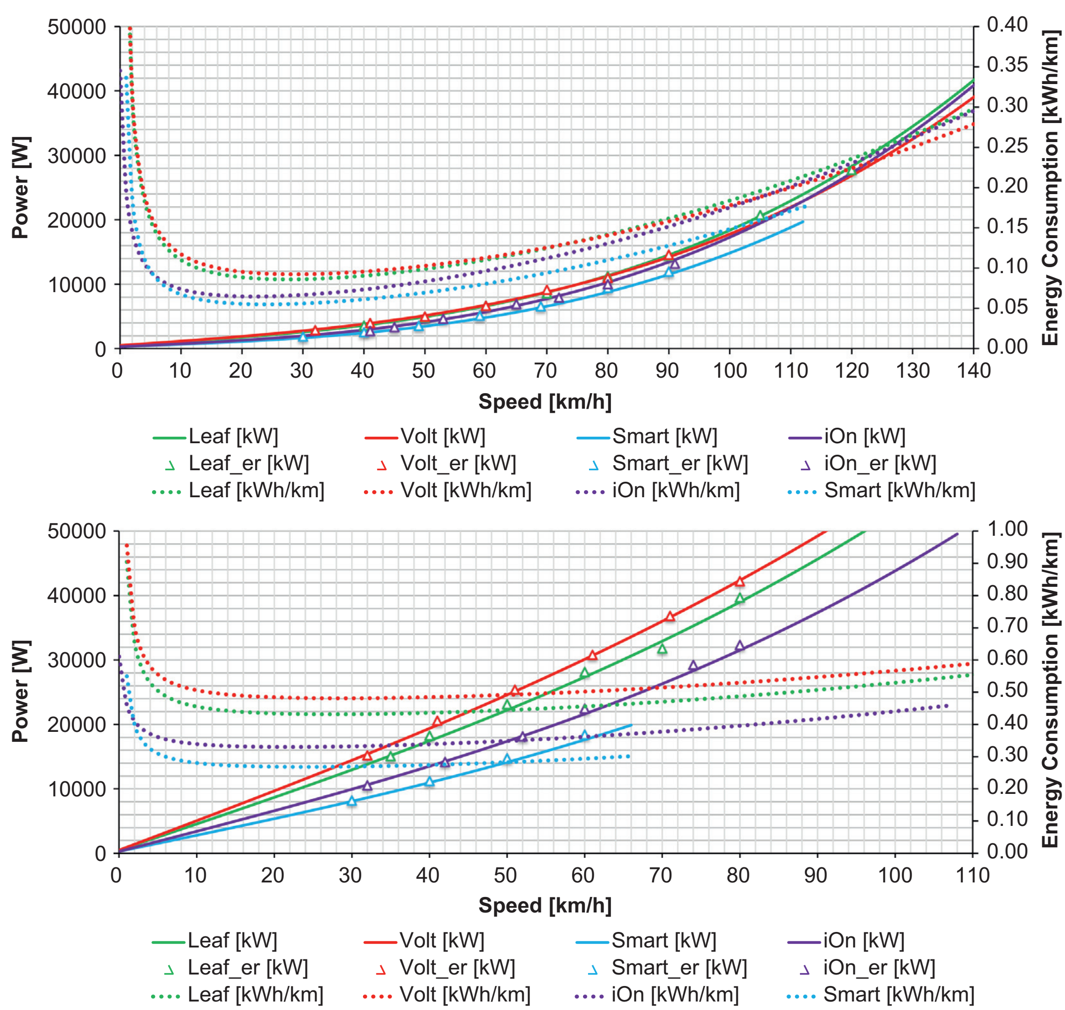

Fig. 4. Power and energy consumption for the Nissan Leaf, Smart ED and Chevrolet Volt for a 0° (top) and 7.2° (bottom) slope. Some data points from experimental runs are identified with the subscript$_{_er}$ with an error of less than 5% when compared with the mathematical model from Eq. (7).

In the case of EVs, since they are equipped with an electric motor that can work as a generator, they can recharge the battery when going downhill or during the braking phase, reducing the overall energy consumption, aspect that is not taken in to account in drive cycles suitable for ICEVs.

In order to assess the energy consumption, and associated GHG emissions, a data acquisition system was developed and installed in the EVs considered in the study. The system was constituted by a 6 degrees of freedom XSens MTI-g Inertial Measurement Unit (IMU), with a three axis accelerometer, gyroscope, magnetometer, GPS and barometric sensor for instantaneous velocity and position measurements; a Fluke i410 current clamp and a Metex M3640D multimeter for instantaneous power measurements, both connected to a computer, through RS-232 for data logging up to 10 Hz (Fig. 3).

Using this data acquisition system it is possible to correlate the energy consumption with the road profile and with the driving profile. This system also allows the breakdown of the instantaneous power consumption into the power required to overcome the forces actuating on the vehicle. A moving vehicle, at a given speed, requires power to overcome the following forces: aerodynamic drag, rolling resistance, gravity when ascending a slope

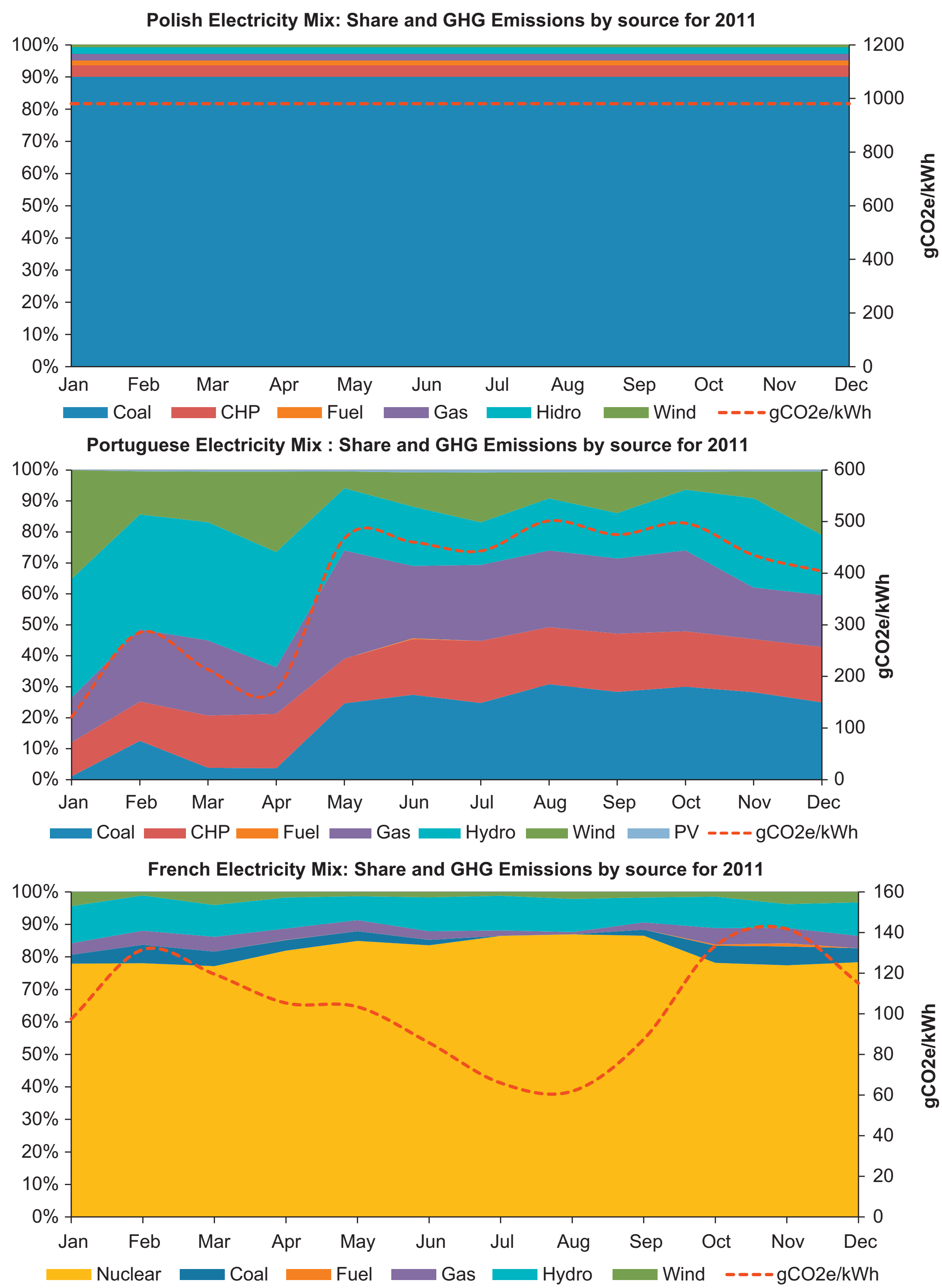

Fig. 5. Electricity mixes share and associated GHG emissions.

and vehicle inertia when accelerating given by Eqs. (3), (4), (5) and (6) respectively:

$$P_{drag} = \frac{1}{2} \cdot \rho \cdot Cd \cdot A \cdot (v - v_{wind})^3 \tag{3}$$

$$P_{roll} = m \cdot g \cdot v \cdot Crr \cdot \cos(\alpha) \tag{4}$$

$$P_{slope} = m \cdot g \cdot v \cdot \sin(\alpha) \tag{5}$$

$$P_{acc} = m \cdot a \cdot v \tag{6}$$

where Crr is the rolling coefficient, Cd is the drag coefficient, ρ is the air density, m is the vehicle mass, A is the vehicle frontal area, v and v_{wind} correspond to the vehicle and wind velocity respectively, a is the vehicle acceleration, g is the gravity acceleration and α is the terrain slope, in degrees.

Eq. (7) represents the total power required to overcome the forces acting over the vehicle considering the motor and transmission efficiency and the auxiliary power, denoted by P_{aux}, required for the control equipment, radio, lights etc.

$$P_{total} = \frac{P_{acc} + P_{slope} + P_{drag} + P_{friction}}{\eta_{motor} \cdot \eta_{trans}} + P_{aux} \tag{7}$$

On Fig. 4 the comparison between the EVs in terms of power and energy consumption in for a flat road profile is presented. Due to a lighter weight, the Smart ED is vehicle with the lower energy consumption followed by the Nissan Leaf and by the Chevrolet Volt, however at higher speeds the Chevrolet volt requires less power and consequently less energy due to a better aerodynamic coefficient (Cd) when compared with the Nissan Leaf (0.28 and 0.29 respectively).

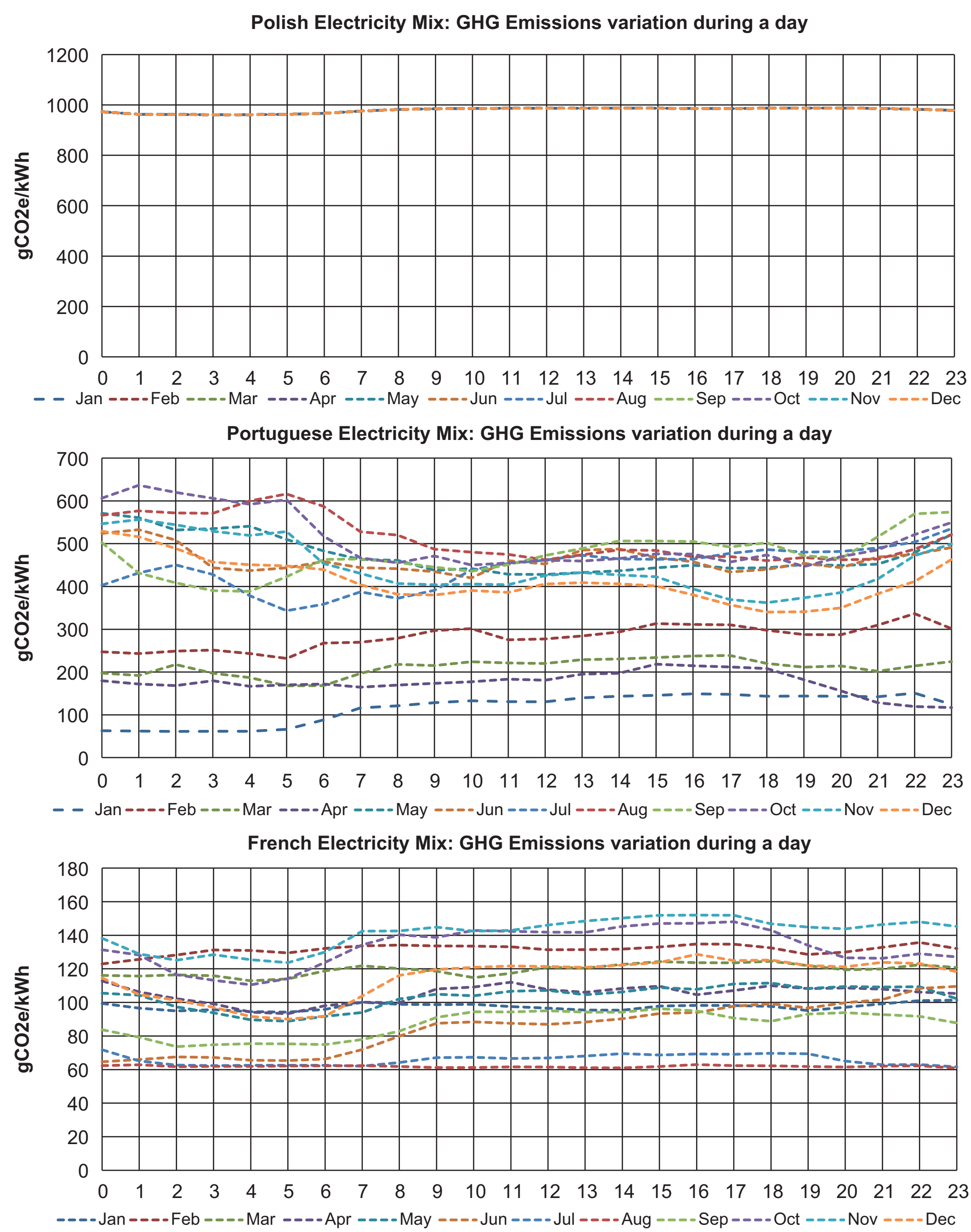

Fig. 6. Average GHG emissions variation during the day, over a year, for the considered mixes.

2.3. Energy sources: emissions assessment

2.3.1. Crude oil extraction and refining

In Europe, transport is responsible for almost 20% of the GHG emissions, with 930 $MTCO_{2e}$ in 2010 according the Eurostat latest data, with passenger cars contributing with almost 12%. EU transport emissions currently contribute with 3.5% of the global CO_2 emissions. Relative CO_2 emissions from transport have decreased over the past years, from 2005 to 2010 they decreased 3.4% despite the increase of 5% in the motorization rate during the same period, due to a proposed a legislative framework to reduce GHG emissions from the transport sector [57,58].

The International Energy Agency (IEA) predicts that the crude oil consumption will increase 27% until 2030, from 83 MMbbl/d (million barrels of oil per day), in 2009, to 102 MMbbl/d, in 2030. Crude oil extraction, transport and refining, accounts in average, for about 18% of WTW of GHG emissions [59]. The quantification of the WTW emissions is divided into five components associated with the petroleum production: (i) extraction, (ii) flaring and venting, (iii) fugitive emissions, (iv) crude oil transport and (v) refining.

In Europe the crude oil comes from a large number of oil fields around the world and each of them has specific GHG emissions, depending on the type. The carbon intensity of crude oil ranges from 4 to 50 gCO_{2e}/MJ (grams of CO_2-equivalent per megajoule), with an average of 13 ± 2 gCO_{2e}/MJ [59]. Extraction of crude oil from tar sands, a very energy intensive process, contributing to high GHG emissions and the IEA projects that 8% (8.9 MMbbl/d) of the world crude oil will come from this source in 2035 [60].

Additional emissions from fuel combustion in motor vehicles are about 73 g CO_{2e}/MJ ($\approx$152 gCO_{2e}/km, for gasoline with 34.8 MJ/l and a consumption of 6 l/100 km and $\approx$127 gCO_{2e}/km, for diesel with 38.4 MJ/l and a consumption of 4.5 l/100 km). lifecycle emissions for diesel and gasoline due to fuel burning are around 3200 gCO_{2e}/l and 2900 gCO_{2e}/l respectively.

2.3.2. Electricity mix

Generally the use phase dominates the overall impacts, however, for an electricity mix with a large contribution from RES, the production phase of a BEVis the one that dominates the overall environmental impact [29,61]. To assess correctly the impact of a BEV the electricity mix used to charge the vehicle must be known with a good degree of certainty.

The primary energy source used for electricity generation contributes directly to the overall GHG emissions of the generation mix, which in turn affect the use phase GHG emissions of an EV. Emissions associated with fuel production are more or less constant over time, mainly affected from where the crude oil is extracted, and could be considered over a large geographic area unlike electricity generation that depends directly from the share and type of power plants on the system and could vary significantly from country to country. Other key aspect to take into consideration, is that the share of each type of energy source contributing to the overall electricity mix varies daily and is also dependent on the season [62].

Most studies consider an average electricity mix over a year for a given geographic region that can lead to results, in terms of GHG emissions during a vehicle life-cycle, that do not reflect the reality, since the emissions associated to different charging periods are not constant during the day. One objective of the presented study is to assess the impact of the electricity mix and the EV charging profile in the overall life-cycle emissions. To assess more accurately the contribution from electricity generation to the overall LCA, a WTT analyzes was performed considering the following mixes found in Europe:

- A mix with high GHG emissions represented by Poland.
- A mix with very low GHG emissions represented by France. item A mix with large contribution from RESs represented by Portugal.

On Fig. 5 and on Fig. 6 it is easily noticeable that the mix varies considerably over the year and also during the day, due to the intermittence and share of RESs for the overall electricity generation. This variation is very noticeable in mixes with a large contribution from RESs or Nuclear, such as Portugal and France, where a drop in the contribution from RESs must be compensated by using fossil powered plants, leading to higher overall GHG emissions [63]. In a mix mainly ruled by fossil fuel powered power plants, the associated GHG emissions are fairly constant over the year and over the day. This type of mix has the higher associated emissions with an average value of 979 gCO_{2e}/kW h over the year, while the Portuguese and French mix had an average value of 376 and 103 gCO_{2e}/kW h respectively. It should be noted that for the case of Poland due to a high share of fossil fuel powered power plants and low variation in the electricity mix during the year, the data for a typical month was considered for all year.

The GHG emissions were calculated taking into account the standard emissions from Table 3 [64].

2.3.3. Contribution of the RESs to the reduction of GHG emissions over the next decade in the European Union (EU)

The European Commission (EC) is committed to reduce the GHG emissions to 80–95% bellow 1990 levels by 2050 and the investment in RESs is seen as a key factor for the decarbonization objective while at the same time reducing the dependence from fossil fuel sources and ensuring security of energy supply. According to the National Renewable Energy Action Plans, in a reference scenario, is estimated that the RESs in EU will contribute with 25% in 2015 and 31% in 2020. In an increased energy efficiency scenario, the contribution from RES is expected to be 26% in 2015 and 34% in 2020 [65]. Projections estimate that RES contribution will increase to 902 TW h, a 32% growth, by 2015 and to 1216 TW h by 2020, a 87% growth, from the 2010 652 TW h. Between 2010 and 2020, the RESs with the highest growth in terms of installed capacity will be solar, with a 250% growth, and wind, with a 151% growth. In 2020, hydro and wind will continue to be the sources with the highest share, both in terms of installed capacity and electricity generation, with 495 TW h and 370 TW h respectively. This increase in the share of RESs in the total electricity generation, to 30–40% in 2020, will lead to a reduction in the electricity mix emissions of 14–66 gCO_2/kW h from the 312–364 gCO_2/kW h in 2009. Additional measures to promote energy efficiency will lead to additional reductions. Due to this fact

Table 3
Typical lifecycle GHG intensity by type of generator [64].

Technology	Emissions (gCO_2 e/kW h)	Observations
Coal	1050	Without scrubbing
Coal	960	With scrubbing
Wind	9–10	
Hydroelectric	13	Run of river
Hydroelectric	10	Reservoir
Biomass	14–41	
Solar PV	32	Polycrystalline silicone
Nuclear	66	
Natural gas	443	
Diesel oil	778	
CHP	354	

the EV is the only vehicle that gets cleaner, due to an increasingly cleaner energy source, during its life-cycle.

3. Life-cycle GHG emissions

Fig. 7 presents the life-cycle GHG emissions for each vehicle technology. The emissions for the EVs were calculated based on the WTW efficiency and on the average electricity mix emissions for 2011 (979 gCO_{2e}/kW h for the Polish mix, 376 gCO_{2e}/kW h for the Portuguese mix and 103 gCO_{2e}/kW h for the French mix). The results show that the overall emissions from EVs are highly dependent on the electricity mix. The Chevrolet Volt shows higher GHG emissions than conventional Internal Combustion Engine (ICE) technology. The additional weight of PHEVs due to the two engines has a negative impact since more energy is required to move the vehicle. On the other hand, the Smart ED shows the lower GHG emissions since it is the lighter of the EVs analyzed. As expected, charging an EV with an electricity mix with lower GHG emissions reduces significantly the overall life-cycle emissions. In this case, the PHEV Chevrolet Volt can have overall emissions similar to a sub-compact conventional vehicle, the Smart diesel, despite their significant weight difference.

Fig. 8 presents the share of the life-cycle emissions by vehicle category, for each vehicle technology and electricity mix. For the Internal Combustion Engine (ICE) conventional technology, the dominant phase is by far the operation phase, accounting for 85–90% of the global emissions, mainly associated to fuel combustion. For EVs, the battery production accounts for a large share of the emissions, almost the same as vehicle production, due to the highly energy intensive processes required to obtain the materials used in the battery production. The emissions from operation phase are highly dependent on the electricity mix. In a mix heavily dependent on fossil energy sources, such as the Polish mix, the use phase account for 70–80% of the overall emissions. For an electricity mix with lower GHG emissions, such as the French mix where the generation is mainly from nuclear, the production phase is the most significant to the overall emissions, accounting for around 70–75%.

GHG emissions from maintenance and vehicle disposal represent less than 10% of the overall emissions. Despite EVs having less maintenance compared to conventional vehicles, the share associated with maintenance will be higher since they have lower emissions. Additional emissions for the disposal of the battery should also be taken into account. However, it should be noted that batteries still retain some capacity at the end-of-life, and, thus, can be reused on other applications such as static energy storage, where the requirements are more flexible thus extending their useful life.

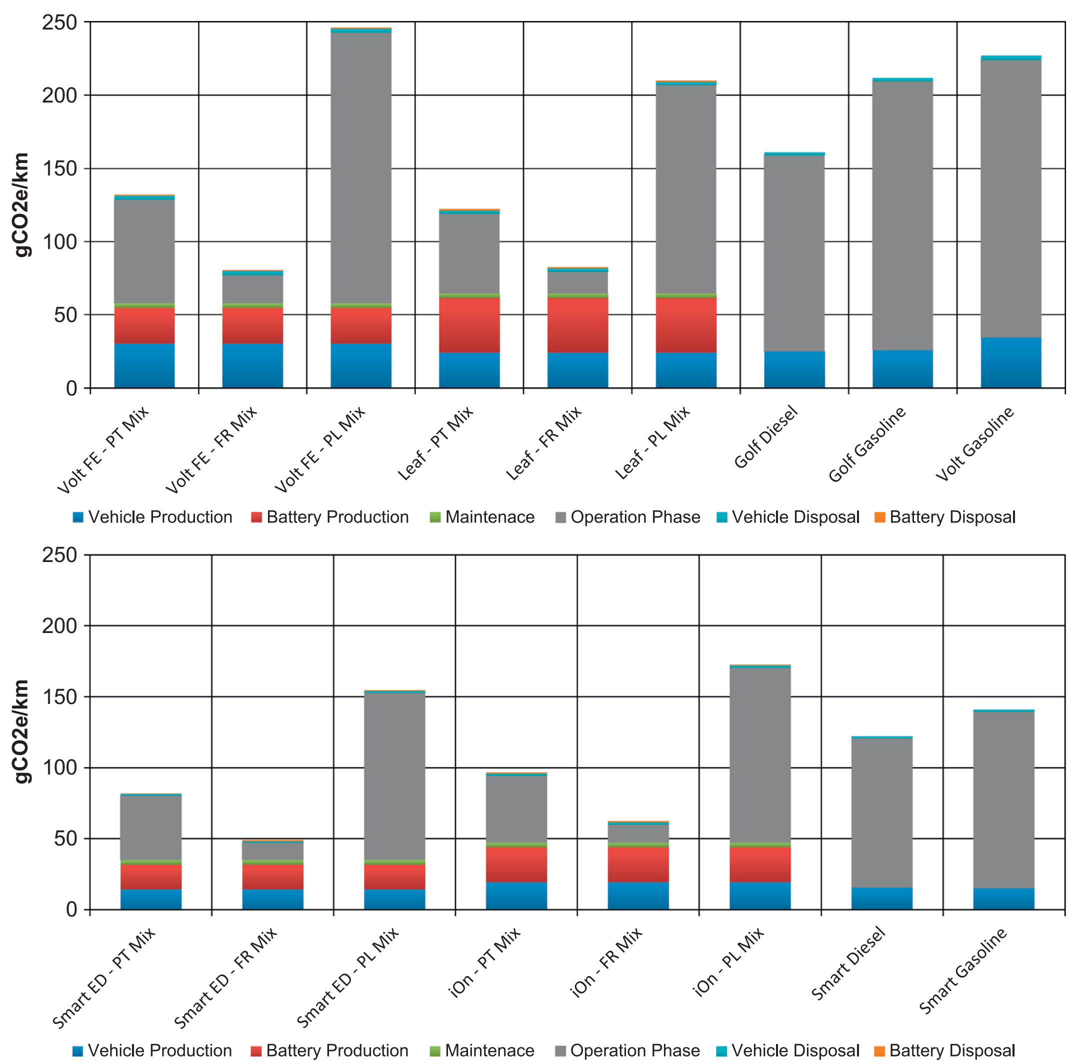

Fig. 7. GHG intensity per km traveled and by electricity mix considered (top: compact vehicles; bottom subcompact vehicles) category. *Note*: In the case of the Chevrolet Volt, the FE denominates the full electric mode.

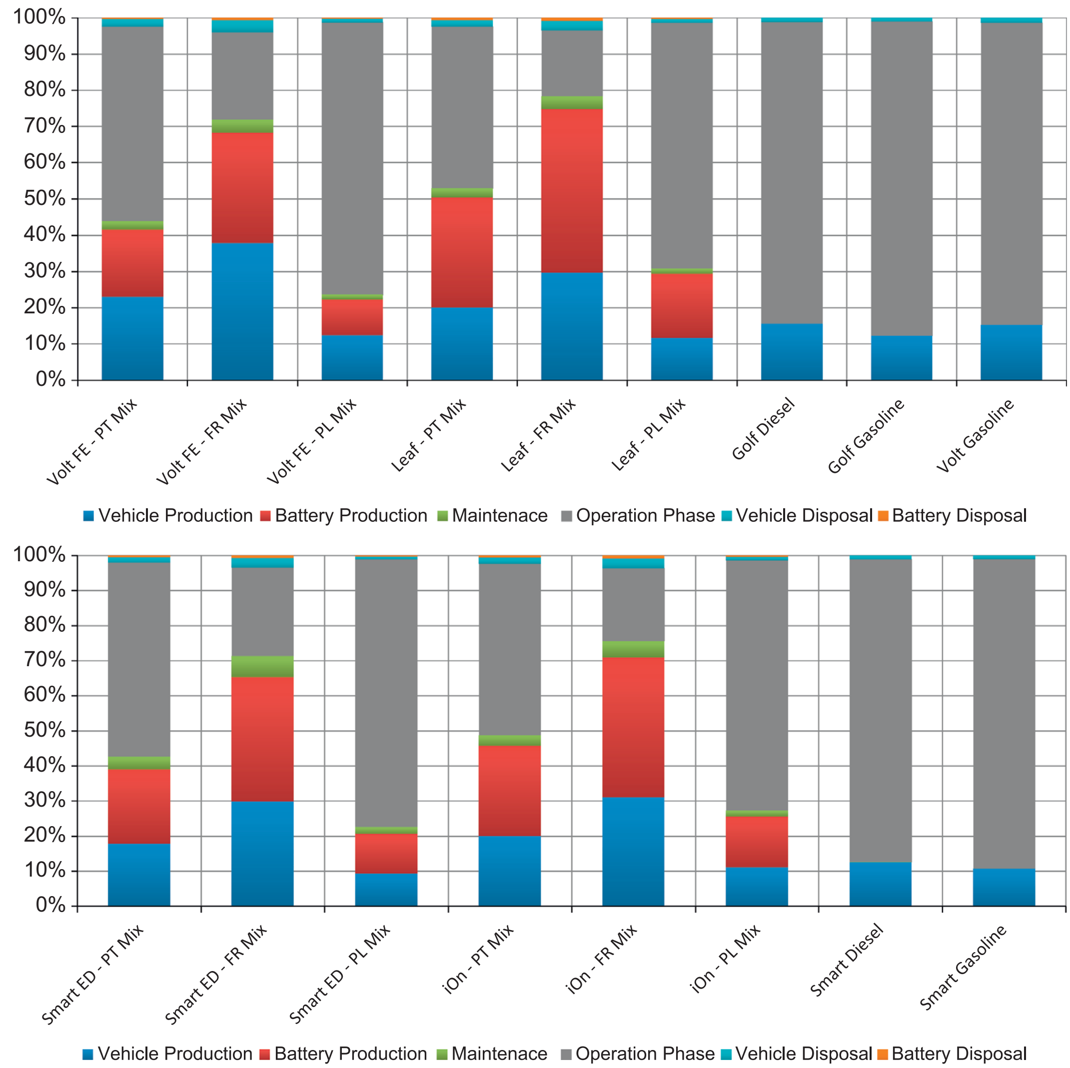

Fig. 8. Conventional and electric vehicle technologies GHG emissions by share and by electricity mix considered, divided into compact (top) and subcompact (bottom) category. *Note*: In the case of the Chevrolet Volt, the FE denominates Full Electric mode.

3.0.4. Impact of the vehicle charging profile on the overall GHG emissions

As stated before the emissions associated with the electricity mix vary significantly during the year and even during the day. These variations are associated with the intermittent nature of the renewable resources. In this case, some conventional power plants, powered by fossil fuel, must be in standby increasing the overall emissions associated to electricity generation. In Autumn and Winter the contribution from RESs is significant due to the rainy and windy nature of these seasons. However due to the variations of the weather conditions between years this is not always verified.

Other aspect that influences the overall emissions for a given vehicle is when the vehicle is charged on a daily basis. This is more relevant for electricity mixes with a large share of RESs. For mixes with a large contribution from fossil or nuclear sources, such as Poland or France respectively, the emissions from electricity generation are more stable. However, in the case where RES represents a large share of the electricity mix this is not always true due to different levels of renewable generation available at each hour. Since coal and gas fueled power plants require a significant start up time, that can go up to 8 h, they must be kept at a minimum level of operation independently of the consumption. This aspect is visible where was cleaner to charge an EV during the day rather at night for several months for the Portuguese electricity mix during 2011 (Fig. 10). For a mix were the main share of RES is hydro and wind such as Portugal, during winter months, charging at night will emit approximately less 20–50% when compared with a charge during the day. For summer months, this situation is not always true, as for some months charging during the day will emit approximately less 4–23% when compared with a night charge.

For mixes with a large contribution from fossil or nuclear power, the emissions variation during the day from electricity generation are not usually significant (Figs. 9 and 11), except in winter months, meaning that charging at night or during the day will not have a major impact on the overall emissions. However the best time to charge an EV is at night, since the energy consumed by the EV will contribute to a flatter load profile and also to maximize the amount of time that power plants remain closer to their nominal capacity.

3.0.5. Impact of the vehicle driving profile on the overall GHG emissions

To assess the impact of the driving profile several real world driving cycles were performed in two predefined routes, one

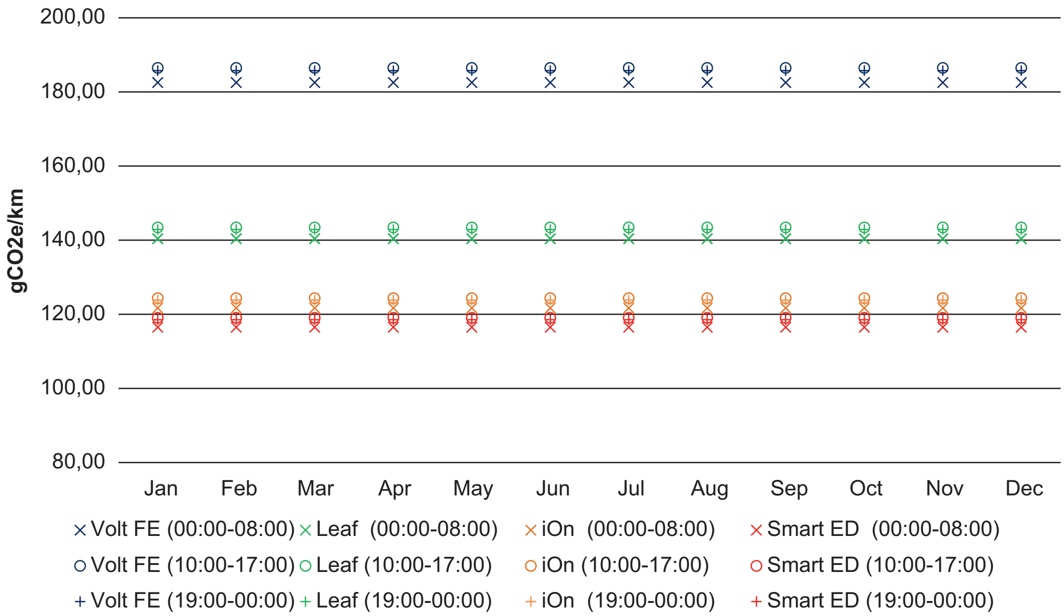

Fig. 9. GHG emissions associated to the operation phase, for the considered EVs, based on the time of day when the vehicle is charged, considering the Polish electricity mix for 2011. Only the emissions during the specified charging intervals were accounted for, emissions during 2 h in the morning and in the afternoon, when the vehicle is being used for commuting, were not accounted.

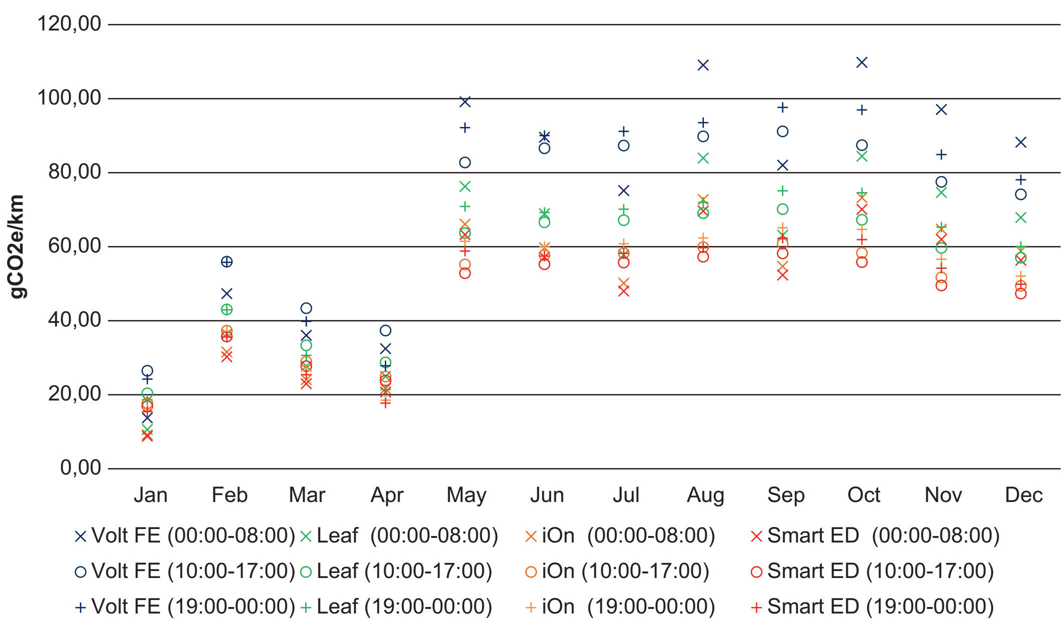

Fig. 10. GHG emissions associated to the operation phase, for the considered EVs, based on the time of day when the vehicle is charged, considering the Portuguese electricity mix for 2011. Only the emissions during the specified charging intervals were accounted for, emissions during 2 h in the morning and in the afternoon, when the vehicle is being used for commuting, were not accounted.

urban and other suburban, under different driving conditions (aggressive, normal and ECO) and with different settings for the climate control (A/C OFF, A/C in cooling mode and A/C in heating mode).

The aggressive driving profile differs from the normal driving profile mainly in the acceleration and braking phase, where the aggressive has fast accelerations and sudden braking to maximize the energy consumption. The ECO driving profile is characterized by slow accelerations, lower top speed and the braking is mainly due to the regenerative braking, to minimize the overall energy consumption. For the driving cycles, the climate control was set in manual mode at 21 °C with the fan at medium speed, both for cooling and heating, being the baseline with the climate control OFF. The use of a manual setting for climate control allows a better understanding about how it can affect the overall energy consumption and associated emissions. Fig. 12 shows the elevation profile for the urban and extra urban routes used to assess the EV energy consumption.

The data was captured using the data acquisition system from Fig. 3. On Table 4 some results of the runs performed under different conditions and with different settings for climate control are presented. In this section, all the presented results refer to trials performed with a Nissan Leaf. The remaining EVs considered along the paper will have a similar results but referred to their specific energy consumption for the presented scenarios, by a weighting factor.

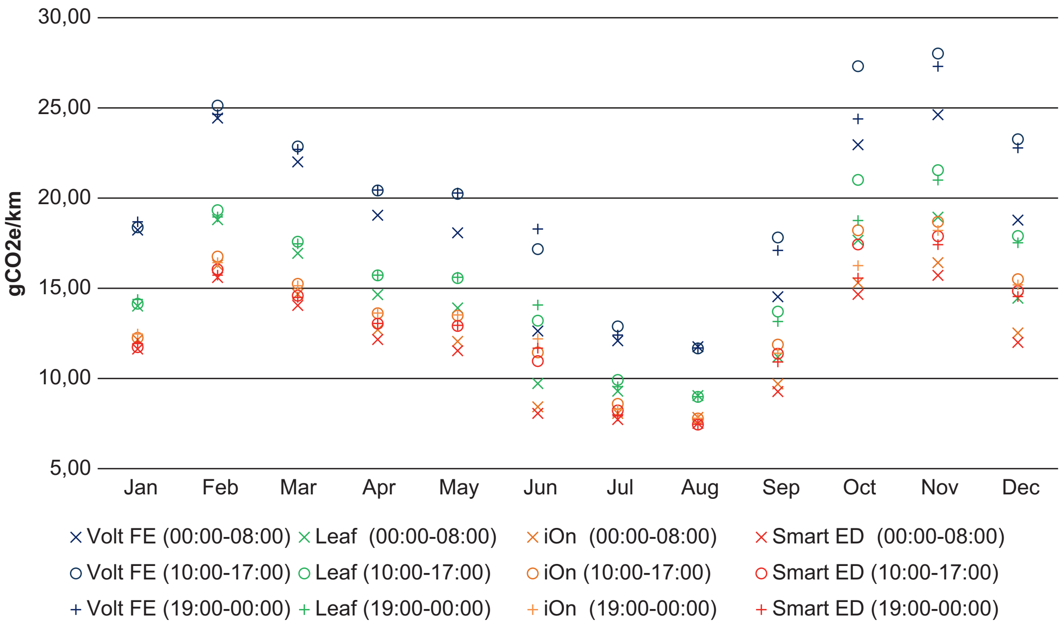

Fig. 11. GHG emissions associated to the operation phase, for the considered EVs, based on the time of day when the vehicle is charged, considering the French electricity mix for 2011. Only the emissions during the specified charging intervals were accounted for, emissions during 2 h in the morning and in the afternoon, when the vehicle is being used for commuting, were not accounted.

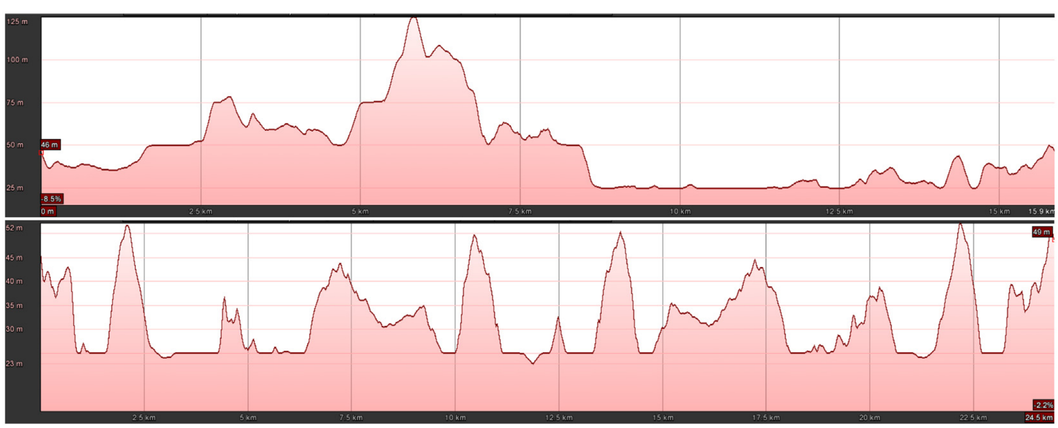

Fig. 12. Urban (top) and extra urban (bottom) elevation profile for the two routes considered in this study to assess the driving profile impact in the overall EV energy consumption.

Table 5 summarizes the average energy consumption and estimated range for the considered scenarios while Table 6, based on the energy consumption, shows the associated emissions by scenario and electricity mix. As expected, an economic driving profile is more efficient than an aggressive one, which can reduce the driving range by 90 km due to the increased energy consumption in 47%. The use of climate control also has a significant impact, increasing the energy consumption in 24% in cooling mode and 61% in heating mode for the ECO driving profile.

In Fig. 13 is possible to compare the impacts, per km traveled, due to different driving profile and the use of climate control against a baseline scenario, for the considered electricity mixes. For an electricity mix with low GHG emissions the way an EV is used will not affect the life-cycle emissions in a significant way. However for an mix with high GHG emissions this is no longer valid. As the electricity mix associated GHG emissions increase, more relevant will be the impact of the use profile of the EV. Fig. 14 correlates the vehicle energy consumption (in Wh/km), directly related with the emissions per km traveled (in gCO_{2e}/km), and the electricity mix life-cycle emissions (in gCO_{2e}/kW h) on the EV overall life-cycle GHG emissions.

4. Life-cycle ownership costs

From a consumer stand point a key aspect of EVs is how much will a given technology cost during its life-cycle. To evaluate it, an economic assessment for each vehicle technology during the full life-cycle was performed, intending to estimate the cross point in time which a given vehicle technology takes advantage over another. For the economic analysis the purchase, operation, depreciation and capital cost was considered based on EU market and manufacturer data.

The operational cost, per year, was calculated based on a total driven distance of 20 000 km and the average fuel and electricity prices in EU in 2012 (1.42€ for diesel, 1.51€ for gasoline and 0.17€/kW h for electricity) [66]. It should be noted that in certain countries the electricity cost varies with the hour of the day.

Table 4
Results for the Nissan Leaf real world driving cycles, for urban and extra urban routes, under different driving profiles and climate control settings.

Type	Length (km)	Energy consumption (Wh/km)			Speed (km/h)	
		AC OFF	AC ON Cool.	AC ON Heat.	Max./ Median	Driving profile
Urban	16	155.4	177.7	213.4	86/43	Aggressive
Urban	16	126.6	148.1	182.3	86/47	Normal
Urban	16	95.5	122.2	164.8	61/42	ECO
Urban	17	135.1	153.7	183.2	96/58	Normal
Urban	17	103.9	128.5	167.8	82/45	ECO
Urban	16	114.9	135.6	168.6	71/42	ECO
Extra Urban	16	157.2	172.7	197.4	115/63	Aggressive
Extra Urban	16	143.0	157.3	180.1	100/67	Normal
Extra Urban	16	138.1	154.5	180.6	85/70	Normal
Extra Urban	16	132.8	148.3	173.0	100/77	ECO
Extra Urban	16	129.3	145.0	170.0	100/60	ECO

Table 5
Energy consumption and estimated range for the Nissan Leaf based on the driving profile and climate control settings based on data acquired from several runs in a urban and suburban environment.

Driving style	AC OFF		AC ON Cool.		AC ON Heat.	
	Wh/km	km	Wh/km	km	Wh/km	km
Aggressive	155.4	129	177.7	113	213.4	94
Normal	131.0	153	151.0	132	182.8	109
ECO	104.7	191	129.0	155	167.1	120

Table 6
Estimated GHG emissions for the Nissan Leaf, per km traveled for the operation, based on the driving profile and climate control settings, for the considered electricity mixes. The emissions considered, for each mix, were the average values for 2011 (979 gCO_{2e}/kW h for the Polish mix, 103 gCO_{2e}/kW h for the French mix and 376 gCO_{2e}/kW h for the Portuguese mix).

Driving style	AC OFF			AC ON Cool.			AC ON Heat.		
	PL Mix	PT Mix	FR Mix	PL Mix	PT Mix	FR Mix	PL Mix	PT Mix	FR Mix
Aggressive	177	68	19	202	78	21	243	93	26
Normal	149	57	16	172	66	18	208	80	22
ECO	119	46	13	147	56	15	190	73	20

In Portugal during the day (08:00 h–22:00 h) the electricity costs 0.14€/kW h while at night (22:00 h–08:00 h) it costs 0.08€/kW h, which translates to a 43% reduction in the electricity cost per year only by charging the EV at night. Other operational costs such as maintenance and insurance were also considered for each vehicle based on market and manufacturer data. An inflation and interest rate of 2.5%/year and 5%/year, respectively, were also considered. The use scenario considered for the PHEV was 80% in electric mode, for commute during the week, and 20% in extended range mode for longer trips. Table 7 summarizes the costs associated to each vehicle used to calculate their annual operational costs.

Fig. 15 shows that EVs have lower costs than conventional vehicles, due to a simpler maintenance and the equivalent electricity cost required to travel a given distance is much lower than gasoline and diesel. The PHEV has a higher maintenance cost due to the combustion engine, however lower than ICEVs. The main costs during the lifetime of EVs are the initial investment and associated interest, accounting around 70–80% of the total life-cycle costs, while for conventional vehicles they only account up to 50%.

From Fig. 16 it is possible to estimate the break even point for each EVs when compared with a conventional vehicle. Due to the higher initial cost of an EV the turn around time could be up to the entire life-cycle of the vehicle (9–10 years), despite their lower operational cost. This is even worst for the PHEV since it has two types of drivetrains, a conventional and an electrical one, making it the most expensive version of all of them. As expected, the cheapest EV is the Smart ED, because of its lower initial cost, but it should be noted that this vehicle is in a different category from the rest in terms of capacity.

5. Conclusion

With vehicle emissions becoming stricter over the next decade due to governmental requirements to mitigate global warming and local pollution, as well as the requirements to improve fuel economy, manufacturers are continuously improving ICE technology and are also developing new technologies such as BEV, Hybrid Electric Vehicle (HEV), PHEV and HFCV. The market viability of BEV and PHEV is highly dependent on the TCO and how the costs are distributed along the vehicle lifetime. For these vehicles, the major cost is the acquisition cost in contrast with the lower costs of ICE vehicles, leading to a slow market penetration.

For diesel, gasoline LPG and CNG vehicles, better control over fuel injection, spark timing and a better fuel/air mixture could lead to additional reduction in emissions, by adjusting the fuel burning parameters depending on the vehicle conditions. Advanced gasoline and diesel vehicles, with stop-star capabilities, downsized

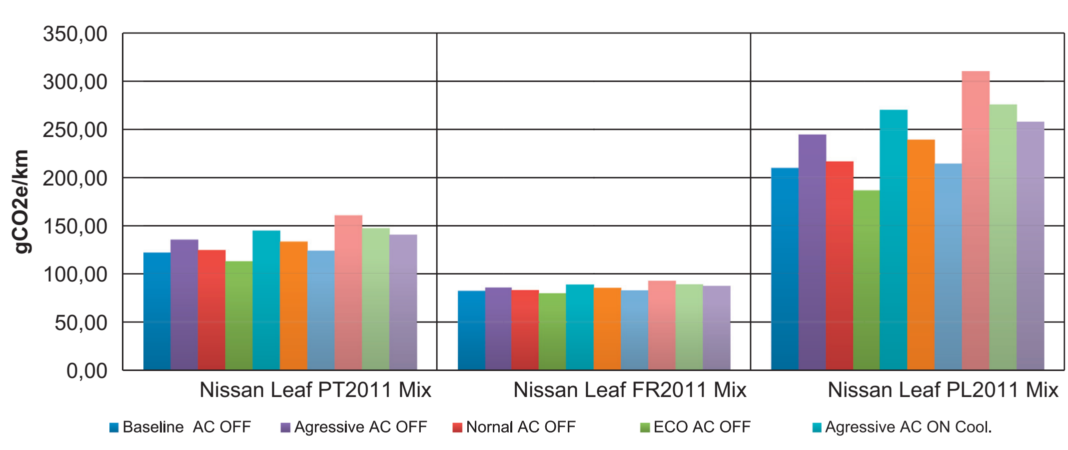

Fig. 13. Impact of the operation phase on the Nissan Leaf on the overall life-cycle emissions per km traveled, by electricity mix. The baseline scenario is based on the range for a full charge provided by the manufacturer (122 gCO_{2e}/kW h for the Portuguese mix, 83 gCO_{2e}/kW h for the French mix and 210 gCO_{2e}/kW h for the Polish mix).

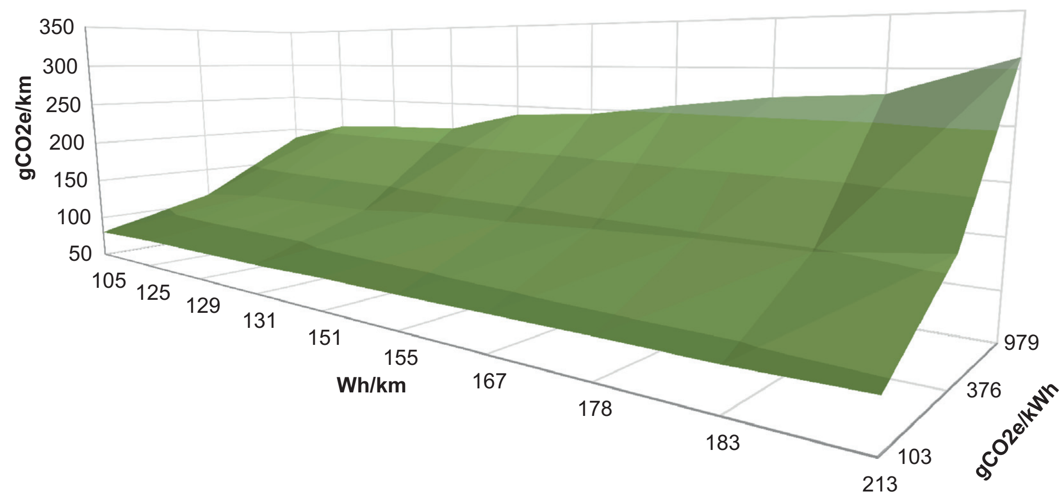

Fig. 14. Variation of life-cycle GHG emissions, per km traveled (based on electricity mix and energy consumption for the Nissan Leaf). The emissions per km traveled take into account the emissions associated with vehicle production.

Table 7
Economic performance for the vehicles considered per year. The considered costs were the investment and ownership costs per year (which include fuel/electricity, maintenance, repair and taxes). All the calculations were based on a driving distance of 20,000 km/year and the average fuel and electricity prices for 2011 in EU (1.42€/l for diesel, 1.51€/l for gasoline and 0.17€/kW h for electricity).

Costs	ICEV				PHEV			BEV		
	Golf 1.6 TDI	Golf 1.4 TSI	Smart CDI	Smart	Volt ED	Volt GD	Volt MD	Nissan Leaf	Smart ED	Peugeot iOn
Investment (€)	22,200	20,300	12,600	9800		42,000		35,000	19,000	30,000
Insurance (€/year)	350	350	350	350		350		350	350	350
Battery leasing (€/year)	–	–	–	–		–		–	720	–
Fuel (€/year)	1192.8	1872.4	937.2	1268.4	–	1932.8	386	–	–	–
Electricity (€/year)	–	–	–	–	552.5	–	442	425	340	368
Maintenance (€/year)	420	380	330	300		335		303	240	280
Operational cost (€/year)	1962.8	2602.4	1617.2	1918.4	1237.5	2617.8	1513.6	1078	1650	998.3

Note: For the PHEV were considered three scenarios: electric drive (ED) powered only by the battery; gasoline drive (GD) powered only by the ICE and mixed drive (MD) powered 80% of the time by battery and the remaining 20% by the ICE.

turbo-charged engines and with some level of hybridization due to the use of an electric motor coupled with small lithium-ion batteries will contribute to additional reduction of vehicles emissions without greatly increasing the cost of ICE vehicles. The use of alternative fuels, such as bio-diesel, ethanol and hydrogen, may also lead to lower life cycle environmental impacts, due to the improvements not only in vehicle technology but also in the fuel production cycle.

The reduction of vehicle weight by using lighter materials is another strategy to reduce energy consumption and GHG emissions which can be implemented independently of the powertrain technology. A breakthrough in carbon-fiber cost would be very valuable, mainly for body parts.

The future of the transport system will pass through the increasing electrification of the powertrain since EVs are more efficient, can be cleaner than ICEVs and significantly reduce the dependence from fossil fuels. Although the payback period could take up to 9–12 years due to the higher initial cost of a BEV or PHEV, the long term EV ownership costs is lower when compared with a conventional vehicle from the same category. Improvements in lithium-ion batteries and super-capacitor technology by using advanced materials will increase their lifetime and efficiency contributing to a longer life cycle and optimizing the battery production will reduce their cost, making EVs more affordable. The second life of EVs batteries, for use in grid storage for instance, will also contribute, to a certain extent, to reduce overall environmental impacts associated to EVs.

Also, the electricity price is also more stable when compared with gasoline or diesel, and with the constant increase in the cost of crude oil the payback period of an EV may be reduced in the future. With improvements in the battery technology, the cost of the EVs will likely decrease, due to the reduction of mass production costs and increased efficiency, making the EV a increasingly attractive choice from the consumer stand point.

For all vehicle technologies analyzed, the operation phase is the one that most contribute to the GHG emissions over the life-cycle of a vehicle, contributing with 85–90% for a conventional vehicle while for an EV this is highly dependent on the electricity mix. For a mix dominated by fossil sources, the operation phase of an EV will be dominant representing more than 75% of the vehicle life-cycle emissions. For a mix with a heavy contribution from nuclear or renewable energy source the dominant phase will be the vehicle and battery production, with at least 50% of the life-cycle emissions, largely dependent on the battery capacity. Other relevant aspect is that an electricity mix with a large contribution from RESs can have significant emissions, during specific periods (hours or days). The intermittent nature of renewable sources requires fossil power to be in standby to take over the generation in the case of failure from the renewable sources.

During the operation phase besides the direct impact of the electricity mix in the overall emissions of EVs, the way the vehicle is operated is a key aspect. A very aggressive driving style, with

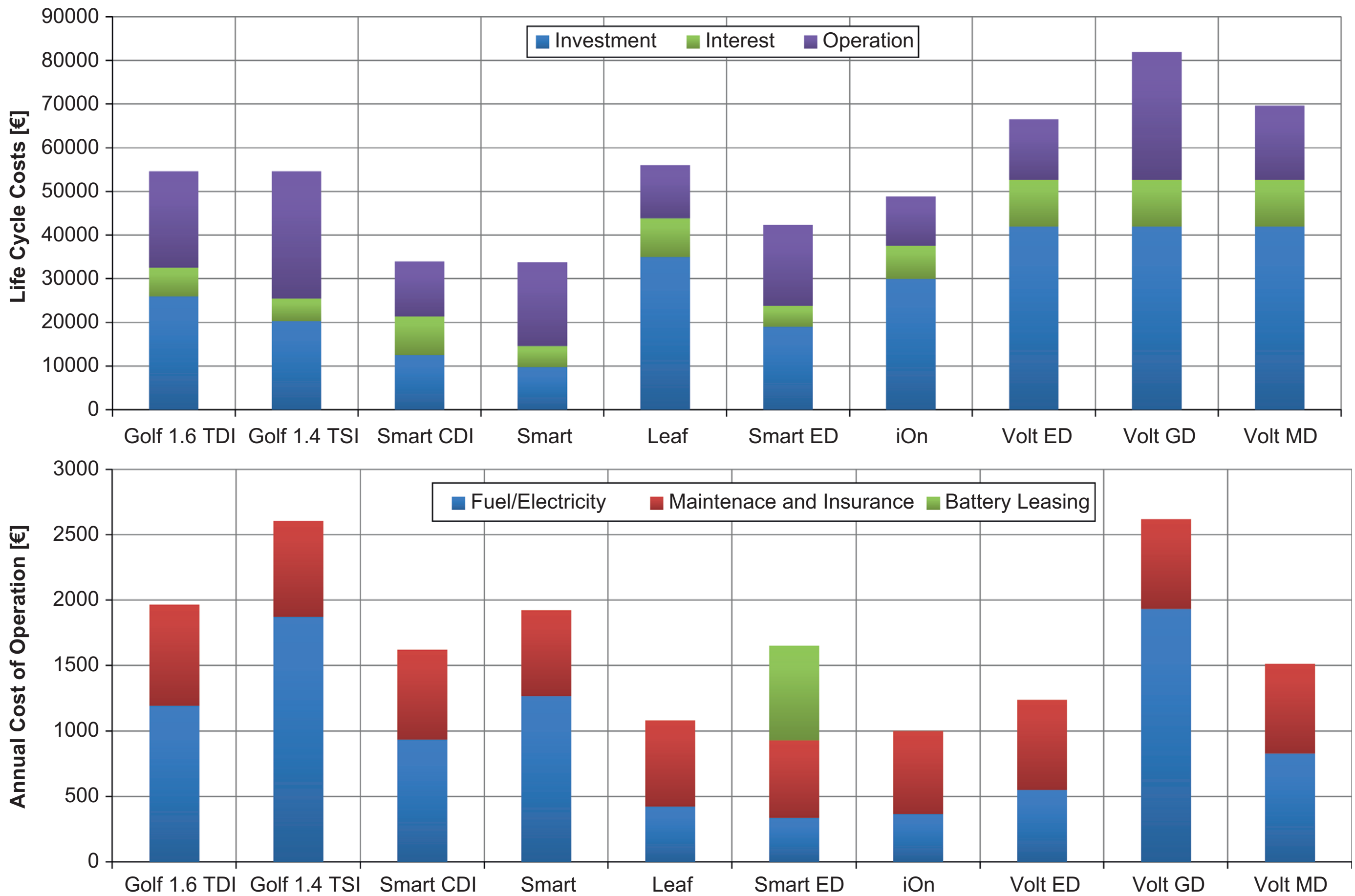

Fig. 15. Total life-cycle costs (top) for the considered vehicles and annual operation cost (bottom). It should be noted that the annual ownership cost does not take into account the inflation rate, however it is considered in the life-cycle costs.

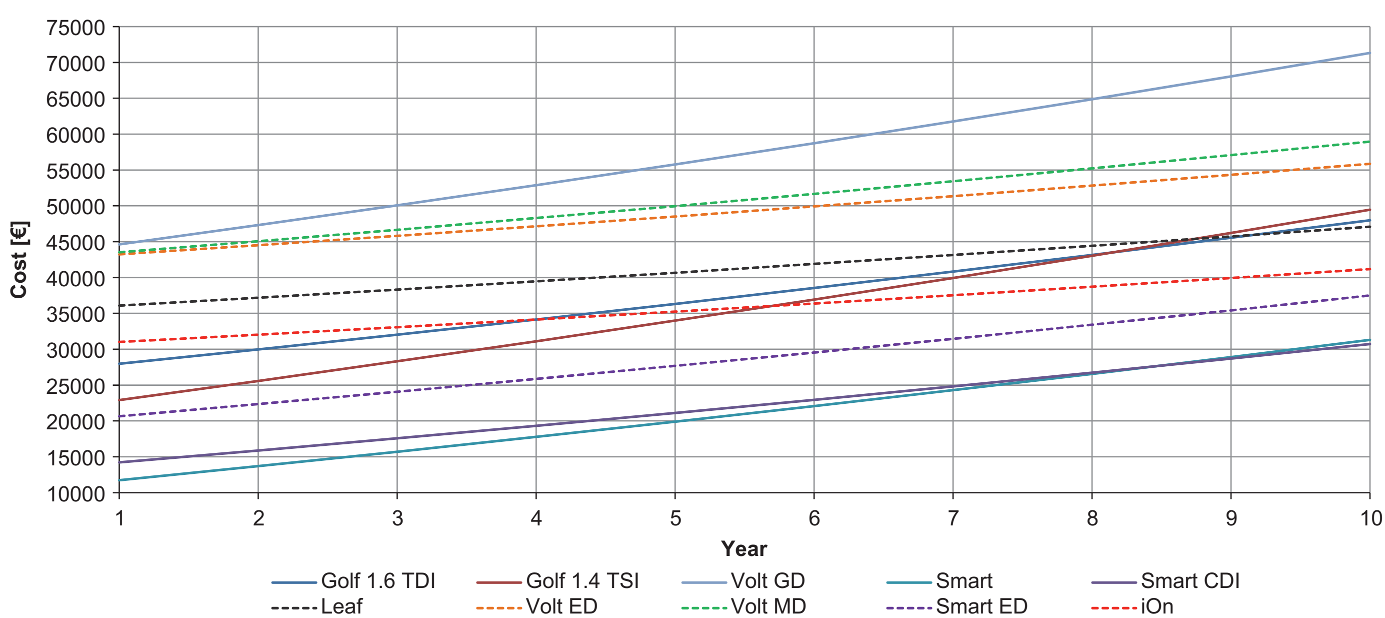

Fig. 16. Cumulative costs of ownership for the considered vehicles during their life-cycle. Only the costs directly associated with the use of the vehicle were considered, depreciation and interests were not taken into account.

fast accelerations and high speed, is directly translated into a reduced range per charge and therefore translated into more emissions due to a higher energy consumption. By increasing the consumer awareness to a more efficient driving style it is possible to achieve, only by itself, significant impact in the reduction of GHG emissions. During the production phase the impacts can be reduced by using recycled materials and replacing certain alloys by composite materials.

Acknowledgments

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